Chapter 3
Stability Requirements

3-1. Philosophy

The philosophy of the structural stability approach contained herein is to establish safety factors or safety provisions for the three prescribed design-load condition categories of usual, unusual, and extreme such that the risk of a failure is kept to an acceptably low level and such that performance objectives are achieved. The use of three different design-load condition categories permits different safety factors or safety provisions to be assigned to the various design-load conditions depending on the probability of the design-load condition occurring during the life of the structure. The design-load conditions used in the stability analyses are described on a probabilistic basis, except the seismic loads falling into the extreme category may be either probabilistic or deterministic. Corps structures, for the purpose of establishing safety factors or safety provisions for use in stability analyses, are to be designated as either critical or normal. Structures designated as critical are those structures whose failure could result in loss of life. All other structures are to be designated as normal. Based on the above definition, the design engineer must determine if the structure is to be designated critical or normal.

a. Load condition categories and performance goals. The load conditions that a structure may encounter during its service life are grouped into the general load condition categories of usual, unusual, and extreme. Associated with each category is a likelihood that the load condition will be exceeded in a given time period. The load conditions, expressed in probabilistic terms, are provided in Table 3-1. The structural performance and the risk of damage or failure depends not only on the likelihood of the loading condition, but also on the safety factors or the safety provisions used, the degree of conservatism used in selecting the strength parameters, and the degree of conservatism inherent in the methods used for the analysis. No attempt has been made to define the likelihood of damage or failure in probabilistic terms. However, the use of these guidelines in conjunction with other Corps guidance will provide structures with protection against stability failure that is equal to other engineered structures regarded as normal or critical structures.

Table 3-1
Load Condition Probabilities

Load Condition	Annual Probability (p)	Return Period (t_r)
Usual[1]	Greater than or equal to 0.50	Less than or equal to 2 years
Unusual[2]	Less than 0.50 but greater than or equal to 0.0067	Greater than 2 years but less than or equal to 150 years
Extreme[3]	Less than 0.0067	Greater than 150 years

(1) In general, *usual* loads refer to loads and load conditions which are related to the primary function of a structure and can be expected to occur frequently during the service life of the structure. A usual event is considered to be a common occurrence and the structure is expected to perform in the linearly elastic range.

(2) *Unusual* loads refer to operating loads and load conditions that are of infrequent occurrence. Construction and maintenance loads, because risks can be controlled by specifying the sequence or duration of activities, and/or by monitoring performance, are also classified as unusual loads. For an unusual event some minor nonlinear behavior is acceptable but repairs, if required following an unusual event, are expected to be minor.

(3) *Extreme* loads refer to events which are highly improbable and can be regarded as emergency conditions. Such events may be associated with major accidents involving impacts or explosions and natural disasters due to

earthquakes or flooding which have a frequency of occurrence that greatly exceeds the economic service life of the structure. Extreme loads may also result from the combination of unusual loading events. The structure is expected to accommodate extreme loads without experiencing a catastrophic failure, although structural damage which partially impairs the operational functions are expected, and major rehabilitation or replacement of the structure is possible.

The load conditions described in Table 3-1 set the return-period ranges for the various loading conditions for which a specified level of performance is expected. For the usual loading condition category, the maximum return period is two years. A normal-pool load condition for instance would be a pool with a mean maximum elevation corresponding to a return-period of up to two years. The unusual category covers a return-period range between 2 years and 150 years. In some cases, a load condition will be defined in terms of a return period. (For example, the Operational Basis Earthquake is defined as an earthquake with a return period of 144 years.) In other cases, a load condition may be stated in nonprobabilistic terms, in which case, the return period must be determined to see if that particular load condition is usual, unusual, or extreme. (For example, pool elevation at the top of closed spillway gates, or another example would be water to the top of a flood wall.) It is not the intent of this guidance to verify stability performance for the unusual load condition for all the various loads (i.e., earthquake, flood,) that have return periods of 150 years, but to use load conditions already established for the various types of Civil Works structures. Definitions of loadings commonly used in the design and evaluation of Civil Works structures are provided in Chapter 4. This includes definitions for the maximum design flood, probable maximum flood, operational basis earthquake, maximum design earthquake, and maximum credible earthquake. Loading conditions for specific structure types are provided in Appendix B. The loading conditions have been taken from other Corps guidance documents and have been modified when necessary to be consistent with other provisions of this manual. Chapter 4 includes figures illustrating the loading conditions for gravity dam spillway monoliths and floodwalls with each loading identified as usual, unusual, or extreme.

   b.   Hydrology/hydraulics risk-based analysis for Corps flood project studies.   Hydrology/hydraulics (H&H) guidance now includes the application of risk-based analysis in the formulation of flood-damage-reduction projects. The requirements are briefly discussed in the next paragraph to familiarize the structural engineer with the procedures H&H engineers use to develop the degree of protection provided by the project (i.e., dam height, floodwall height.) The structural engineer needs to coordinate with the H&H engineers to obtain return periods to determine the probabilities of the applicable load conditions for use with Table 3-1.

   Risk-based analysis quantifies the uncertainty in discharge-frequency, elevation (stage)-discharge, and elevation-damage relationships and explicitly incorporates this information into economic and performance analyses of alternatives. The risk-based analysis is used to formulate the type and size of the optimal structural (or nonstructural) plan that will meet the study objectives. Corps policy requires that this plan be identified in every flood-reduction study it conducts. This plan, referred to as the National Economic Development Plan (NED), is the one that maximizes the net economic benefits of all the alternatives evaluated. It may or may not be the recommended plan based on additional considerations. A residual risk analysis for the NED Plan is next performed to determine the consequences of a capacity exceedence. For a flood-reduction project, the new guidance recognizes that project capacity will be exceeded sometime during its service life. Therefore, the question becomes, "When that capacity is exceeded, what are the impacts, both in terms of economics and the threat to human life?" If the project-induced and/or residual risk is unacceptable, and a design to reduce the risk cannot be developed, other alternatives are further analyzed. Either a larger project, that will ensure sufficient time for evacuation, or a different type of project, with less residual risk, should be selected to reduce the threat to life and property. The H&H design will include measures to minimize the adverse impacts of a capacity exceedence. For channel projects, the final elevation of the top of the wall or levee is set so that initial overtopping will occur at the least hazardous location along the line of protection. This location is usually at the downstream end of the channel, so the protected area will fill in a gradual manner. Also, wall height will be increased at curves in the channel to contain the design water surface profile if super-elevation is a possibility. For reservoirs, a plan is developed so that as the point of exceedence is approached, there is a gradual increase in

outflow from the project to provide time to initiate emergency measures downstream. For a detailed discussion of the H&H requirements, see ER 1105-2-101 and EM 1110-2-1619.
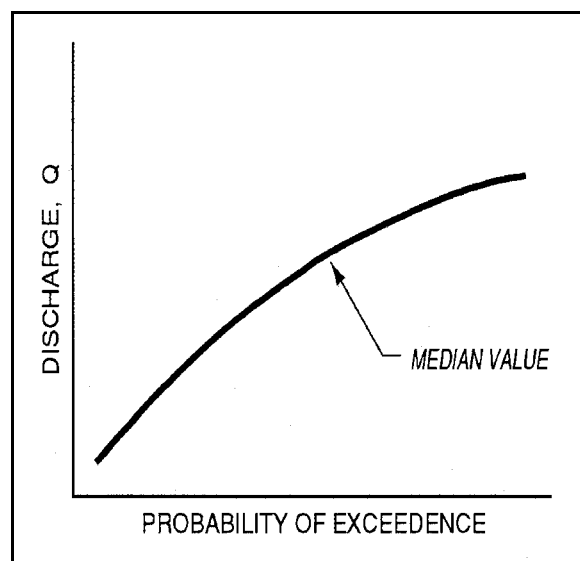

Figure 3-1. Flood discharge versus frequency curve

When the type and size of the project have been selected, detailed design begins. The structural engineer, in coordination with the hydrology/hydraulic engineers, may use expected values (best estimates) of discharge-frequency and stage-discharge curves (Figures 3-1 and 3-2) to estimate return periods for the various prescribed structure-dependent hydrostatic load conditions listed in Appendix B. For load conditions with prescribed headwater/tailwater elevations, (for example, water to the top of closed spillway gates, or water to the top of a flood wall) the headwater elevation may be used in conjunction with the stage-discharge curve and discharge-frequency curves to estimate the annual probability and return period for the event representing the load condition. For some projects, such as high pools at power projects, other information such as project operating data will also be used in estimating the return period for a prescribed loading condition. The designer then refers to Table 3-1 to determine if each particular load condition is usual, unusual, or extreme. Some prescribed load conditions have a specified return period (for example, an operational basis earthquake has a return period of 144 years). In such cases, the structural engineer can determine if the load condition is usual, unusual, or extreme by referring directly to Table 3-1. In some cases, the load conditions are specifically designated as either usual, unusual, or extreme based on established practice.

b.   Existing structures. The safety factors provided in the guidance are based on the assumption that for critical and normal structures, the strength of the materials in the foundation and structure has been conservatively established through explorations and testing. This may not be the case for older existing structures, or, if adequate explorations and testing were performed, the records may not be available. When the stability of an existing structure is in question, a phased, systematic approach to evaluating stability should be performed before any remedial actions are undertaken to improve stability. This systematic evaluation process is described in Chapter 7. The load conditions used to evaluate an existing structure should be carefully checked to make sure that what was considered as a usual load condition for the original design is not, once the probabilities of the load conditions are examined, really an unusual or extreme load condition. When evaluating existing structures, all effort should be made to use analytical methods which accurately describe the behavior without introducing ultra conservatism. When available, actual uplift pressures can be used as a basis for evaluating the stability of existing structures.

c.   Level of knowledge. A proper stability analysis cannot be performed without knowing the potential planes of weakness beneath the structure, the strength of the materials along potential planes of weakness, uplift forces that occur on the structure or on planes of weakness, the strength of backfill materials, and all loads and load conditions to which the structure may be subjected. Knowledge of geologic formations beneath the structure is also important in defining seepage conditions and uplift pressures. Without adequate explorations and testing, a proper stability analysis cannot be performed, and the safety factors provided to assess the adequacy of the structure to resist loads that could cause instability are meaningless. Preliminary stability analyses are useful to identify design parameters which require special attention. In some rock foundations there may be many faults, shear zones, and discontinuities that make it impossible to do little more than predict average shear and cohesive strengths of the materials that make up the foundation. In these cases, conservative strength values should be selected for the stability analyses. Lower
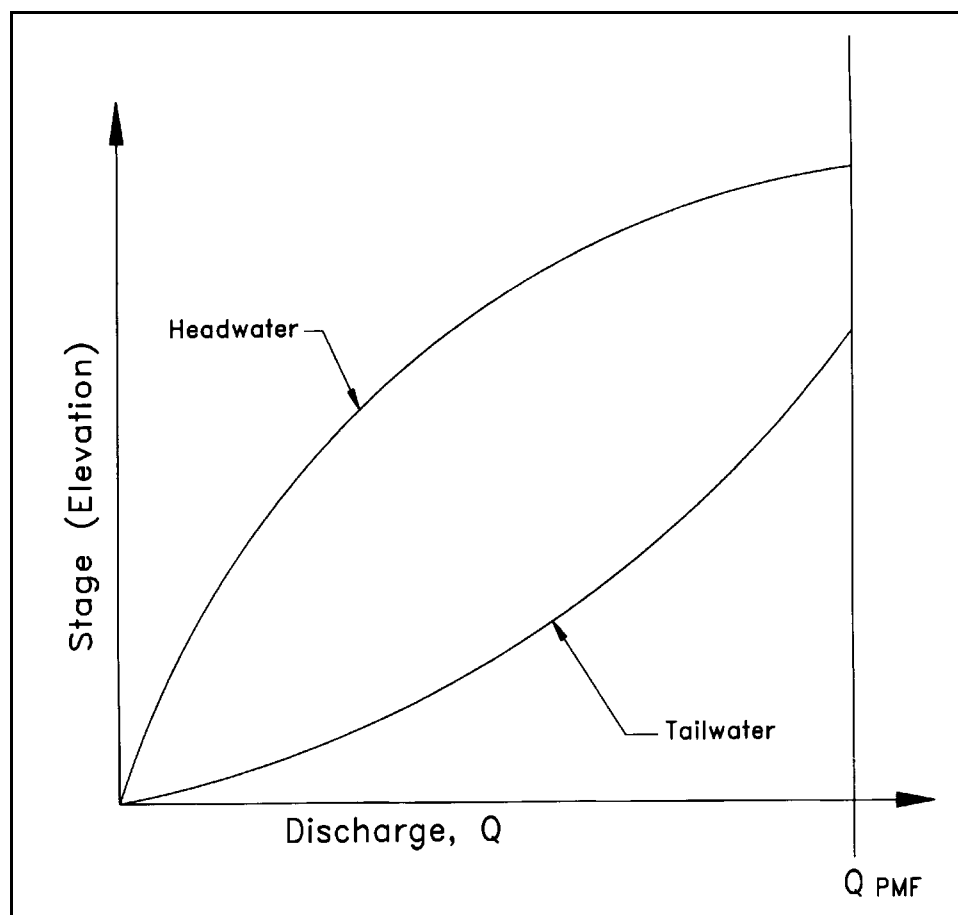
Figure 3-2. Flood stage versus flood discharge curve for dams and appurtenant structures for dams*

factors of safety may be used in cases where there is an abundance of information on the various foundation and structure properties used to establish the strength parameters for the stability analysis. Conversely, higher factors of safety are required when there is only limited information on either foundation or structure properties. The adjustment to the basic stability safety factor to account for the availability of site information is accomplished by using a site information factor (F_{SI}). There is a site information factor given for each of the three categories of *ordinary*, *very well-defined*, and *limited* in Table 3-4.

(1) The *ordinary category* of site information applies when foundation strength parameters have been established in accordance with current Corps exploration and testing procedures that result in a high level of confidence that the design strength parameters accurately represent in situ conditions and represent expected loading conditions, or that the foundation design strength parameters have been based on conservative lower bound values. Also, the ordinary category applies only when design load and load conditions accurately represent the usual, unusual, and extreme load conditions that will occur during the life of the structure, or represent conservative upper bound values for the usual, unusual, and extreme load conditions.

(2) The *very well-defined category* of site information applies to existing structures, where in addition to meeting the requirements of the normal site information category, there are records of construction, operation, and maintenance available that indicate the structure has met all performance objectives and the loads, load conditions, and foundation strengths used for design are conservative.

(3) The *limited category* of site information applies to those cases where the foundation strengths or load conditions cannot be established with a high degree of confidence, or where it is impossible to establish with a high degree of confidence the lower bound values of the foundation strength parameters or the upper bound values of the various usual, unusual, and extreme load conditions.

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*Note: Water surface profiles must be developed by H&H personnel for other project types such as channel and coastal projects.

Use of conservative lower bound values for foundation shear strength or conservative upper bound values for loads is only acceptable when it can be demonstrated that the added costs to improve the accuracy of the strength and loading data will not lead to significant savings for the structure or foundation.

d.   Limit-state approach. The sliding stability analysis procedures described herein, for the most part, are based on a limit state approach which satisfies only some of the equilibrium conditions and only accounts for deformations indirectly. No attempt has been made in this approach to relate shear stresses to displacements; therefore, the shear strengths used for resistance to loads that cause instability may be associated with large deformations. The magnitude of displacement required to reach a limit state needs to be considered when selecting strength parameters. It is not possible, for instance, to develop peak shear and cohesive strength as well as passive resistance, all at the same strain level. The analysis may require the use of residual shear strengths rather than peak shear strength values for this reason. In addition, the deformations associated with shear resistance may be unacceptable for reasons of serviceability, thus requiring higher factors of safety to bring displacements back to levels that will provide a structure that is free from cracks and other damage that would impair its ability to operate at service load conditions as intended. Further discussion of this topic is presented in paragraphs 5-2 and 6-3 below.

e.   Special circumstances. The minimum factors of safety specified herein for sliding stability are based on Mohr-Coulomb limit-state failure criterion without consideration of the deformations that occur in the structure and its foundation, or of the type of failure path the structural system undergoes in reaching a limit-state from a service-state condition. In many cases, it can be demonstrated by the use of finite element analysis and fracture mechanics methods that the factor of safety is substantially different than that predicted by the limit equilibrium method. Under special circumstances, such as in the case of an existing structure where the limit equilibrium method indicates that remedial action is required to improve stability, additional stability analyses may be performed using finite element and fracture mechanics procedures to verify whether stability remediation is actually required. Under special circumstances, and with proper documentation and approval from CECW-ED, the use of alternate numerical methods for assessing the safety of a structure and its foundation may be substituted for the traditional limit equilibrium analysis.

3-2. Factors of Safety for Sliding and Flotation Failure Modes

A factor of safety is required in sliding and flotation stability analyses to provide a suitable margin of safety between the loads that can cause instability and the strength of the materials along potential failure planes that can be mobilized to prevent instability. The required factor of safety for sliding stability is defined by Equation 3-1a, and the required factor of safety for flotation is defined by Equation 3-1b. The required factor of safety is a product of a basic factor of safety (2.00 for sliding and 1.80 for flotation), a loading condition factor (F_L) to account for load condition probability, a structure importance factor (F_I) to account for the different risk levels accepted for critical and normal structures, and a site information factor (F_{SI}) to account for the knowledge of the structure and foundation strength parameters used in the stability analysis. Loading condition factors are provided in Table 3-3, structure importance factors in Table 3-4, and site information factors in Table 3-5.

$$FS_{SL} = 2.00\ (F_L)(F_I)(F_{SI}) \geq 1.10 \tag{3-1a}$$

$$FS_{FL} = 1.80\ (F_L)(F_I)(F_{SI}) \geq 1.10 \tag{3-1b}$$

where

FS_{SL} = required factor of safety for sliding stability

FS_{FL} = required factor of safety for flotation stability

Table 3-2 Loading Condition Factors	
Loading Condition	Loading Condition Factor (F_L)
Usual	1
Unusual	0.875

Table 3-3 Structure Importance Factors	
Importance Classification	Importance Factor (F_I)
Critical Structure	1
Normal Structure	0.75

2.00 = the basic stability factor of safety for sliding

1.80 = the basic stability factor of safety for flotation

F_L = loading condition factor

F_I = Structure importance factor

F_{SI} = Site information factor

a. Sliding stability. Sliding stability is discussed in detail in Chapter 2 and Chapter 5. The factor of safety is defined by Equation 2-7.

b. Flotation stability. Various hydraulic structures are subject to buoyant forces that could cause flotation instability. The flotation factor of safety is defined by the ratio of the forces resisting flotation divided by the forces that cause flotation.

$$FS = \frac{W_S + W_C + S}{U - W_G} \tag{3-2}$$

where

W_S = weight of the structure, including weights of the fixed equipment and soil above the top surface of the structure. The moist or saturated unit weight should be used for soil above the groundwater table and the submerged unit weight should be used for soil below the groundwater table.

W_C = weight of the water contained within the structure

S = surcharge loads

U = uplift forces acting on the base of the structure

W_g = weight of surcharge water above top surface of the structure which is totally controlled by gravity flow

Table 3-4
Site Information Factors

Availability of Site Information	Site Information Factor (F_{SI})
Very Well Defined	0.9
Ordinary	1.0
Limited	2.0

Table 3-5a
Sliding Safety Factors for Critical Structures (F_I = 1)

Availability of Site Information	Usual (F_L = 1.00)	Unusual (F_L = .875)	Extreme (F_L = .667)
Very Well Defined (F_S = 0.9)	1.80	1.60	1.20
Ordinary (F_S = 1.0)	2.00	1.75	1.33
Limited (F_S = 2.0)	4.00	3.50	2.66

Table 3-5b
Flotation Safety Factors for Critical Structures (F_I = 1)

Availability of Site Information	Usual (F_L = 1.00)	Unusual (F_L = .875)	Extreme (F_L = .667)
Very Well Defined (F_S = 0.9)	1.80	1.60	1.20
Ordinary (F_S = 1.0)	2.00	1.75	1.33
Limited (F_S = 2.0)	3.60	3.20	2.40

Table 3-6a
Sliding Safety Factors for Normal Structures (F_I = 3/4)

Availability of Site Information	Usual (F_L = 1.00)	Unusual (F_L = .875)	Extreme (F_L = .667)
Very Well Defined (F_S = 0.9)	1.35	1.20	1.10
Ordinary (F_S = 1.0)	1.50	1.30	1.10
Limited (F_S = 2.0)	3.00	2.60	2.00

Table 3-6b
Flotation Safety Factors for Normal Structures (F_I = 3/4)

Availability of Site Information	Usual (F_L = 1.00)	Unusual (F_L = .875)	Extreme (F_L = .667)
Very Well Defined (F_S = 0.9)	1.20	1.10	1.10
Ordinary (F_S = 1.0)	1.35	1.20	1.10
Limited (F_S = 2.0)	2.70	2.35	1.80

3-3. Safety Provisions for Resultant Location and Bearing Failure Modes

The factors of safety established for sliding and flotation are not appropriate for use in the evaluation of rotational and bearing modes of failure. The resultant location for all vertical forces acting on potential failure planes is used as a basis for rotational evaluation. Allowable concrete compressive stresses and/or allowable bearing values established by materials engineers and geotechnical engineers are used as the basis for evaluating bearing modes of failure.

   a. Resultant location. Through static analysis, the location of the resultant of all forces can be determined with respect to the base of the structure. The location of the resultant of all forces acting on the base of the structure must be such that 100 percent of the base is in compression for usual load conditions, that 75 percent of the base is in compression for unusual load conditions, and that the resultant falls within the base for extreme load conditions. The entire base is to be in compression for the usual load condition so there is no chance for higher uplift pressures to develop in a crack. For the unusual load case, higher uplift pressures may develop in a relatively short crack, but the result will cause only minor nonlinearity in the structure. The extreme load conditions may result in over-stressing parts of the structure and/or foundation but will not cause an overall failure.

   b. Bearing failure. Bearing failure is related to the relative compressibility of the foundation materials, the loading conditions, the geometry of the structure base, and the strength of the foundation and concrete at the structure/

Table 3-7a
Safety Provisions for Critical Structures with Ordinary Site Information

Safety Provisions	Usual Load Condition	Unusual Load Condition	Extreme Load Condition
Sliding Safety Factors	2.00	1.75	1.33
Flotation Safety Factors	1.80	1.60	1.20
Concrete Compressive Stress and/or Bearing Pressure Requirements	Allowable	1.14 × Allowable	1.50 × Allowable
Resultant Location Requirements	100% Compression	75% Compression	In Base

Table 3-7b
Safety Provisions for Normal Structures with Ordinary Site Information

Safety Provisions	Usual Load Condition	Unusual Load Condition	Extreme Load Condition
Sliding Safety Factors	1.50	1.30	1.10
Flotation Safety Factors	1.35	1.20	1.10
Concrete Compressive Stress and/or Bearing Pressure Requirements	Allowable	1.14 × Allowable	1.50 × Allowable
Resultant Location Requirements	100% Compression	75% Compression	In Base

foundation interface. Bearing capacity may be related to the shear capacity of the foundation materials or to the deformability of the foundation. Information on bearing capacity can be found in Chapter 2. Information on foundation bearing analysis can be found in EM 1110-2-2502. Safety against bearing failure is generally expressed in terms of an allowable compressive stress for concrete and an allowable bearing pressure for foundation materials. The allowable compressive stress and bearing pressure values are established by testing performed by materials engineers and geotechnical engineers. The allowable compressive stress and bearing pressure values established for usual load conditions can be increased for the unusual and extreme load conditions by multiplying them by the quantity $1/F_L$, or by 1.14 to get the unusual allowable, and by 1.50 to get the extreme allowable.

3-4. Seismic Stability

Traditionally, the seismic coefficient method has been used to evaluate the stability of structures subjected to earthquake ground motions. This method fails to take into account the true dynamic characteristics of the structure. There have been cases where structures similar to those used on Civil Works projects have failed during earthquakes because of a sliding or bearing failure. These failures for the most part are attributable to liquefaction and soil strength degradation in the foundation or backfill materials. The pseudo-static methods should only be used for screening from further consideration those structures where a seismic stability failure is highly improbable. Structures that fail to meet the prescribed pseudo-static stability requirements referenced herein and in other Corps manuals should not be considered unsafe or in need of a stability retrofit. The failure to meet these requirements should only suggest the need for dynamic analyses that can fairly assess the demands placed on the structure and foundation during a major earthquake, and from the dynamic analyses conclude if the displacements and stresses

experienced by the structure and foundation will place the structure at risk of a stability failure. In many instances, it is acceptable for sliding and rocking to occur at the base of the structure during extreme earthquake load conditions. Stability in such cases is evaluated using dynamic analysis methods, and performance is achieved by limiting permanent displacements to acceptable levels. Guidance on the earthquake design for Civil Works structures is provided in ER 1110-2-1806.

(1) Usual load conditions are maximum design load conditions that have an annual probability of exceedance of 0.50 or more.

(2) Unusual load conditions are maximum design load conditions that have an annual probability of exceedance less than 0.5000 but greater than 0.0067.

(3) Extreme load conditions are maximum design load conditions that have an annual probability of exceedance less than 0.0067.

3-5. Minimum Required Factors of Safety

The following tables furnish criteria check lists for stability analyses considering the loading condition, structure importance, and site information factors for Civil Works structures: Tables 3-5a., 3-5b., 3-6a., 3-6b, 3-7a., and 3-7b.